

Sub two-cycle soliton-effect pulse compression at 800 nm in Photonic Crystal Fibers

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Abstract

The possibility of soliton self-compression of ultrashort laser pulses down to the few-cycle regime in photonic crystal fibers is numerically investigated. We show that efficient sub-two-cycle temporal compression of nanojoule-level 800 nm pulses can be achieved by employing short (typically 5-mm-long) commercially available photonic crystal fibers and pulse durations of around 100 fs, regardless of initial linear chirp, and without the need of additional dispersion compensation techniques. We envisage applications in a new generation of compact and efficient sub-two cycle laser pulse sources.

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I. INTRODUCTION

Over the last twenty years, much effort has been done in generating ultrafast laser pulses in the few-cycle regime. These pulses are behind numerous and important achievements in such diverse fields as the study of ultrafast dynamics in matter, extreme nonlinear optics, high-order harmonic generation, and attosecond physics [1, 2].

Low-energy (nanojoule) sub-2-cycle pulses have been directly produced by state-of-the-art Ti:sapphire laser oscillators [3, 4] where the required ultrabroad bandwidths were achieved by means of double-chirped mirrors that provide high reflectivity bandwidth and tailored dispersion compensation over an extended spectral range. Higher energy pulses (from hundreds of nanojoules up to hundreds of microjoules) have also been produced by passive and/or active phase control of broadband laser sources and of supercontinua generated in Kerr media. These include ultra-broadband optical parametric amplifiers [5], spectrally broadened cavity-dumped oscillators [6], and gas-filled hollow fibers pumped by kHz amplifiers [7, 8] where active compression of the generated broadband spectra has resulted in the shortest (3.4 fs) light pulses to date [9, 10].

However, in all of the above techniques, the possibility of reaching the few-cycle regime relies on sophisticated intracavity or extracavity dispersion compensation schemes, with the latter usually requiring complex electronically-controlled feedback systems.

A different approach to pulse compression relies on the concept of soliton-effect compression of laser pulses, which dates back to the 1980s [11] and has been used to successfully compress low-energy picosecond pulses to durations as short as 18 fs [12] without the need of additional dispersion compensation. This method exploits the peculiarities of high-order periodical soliton propagation in optical fibers in the anomalous dispersion regime, where efficient compression is obtained at the output end of a fiber of properly chosen length. A signature of this process is the appearance of a broad pedestal, which for relatively long pulses (> 100 fs) can be efficiently suppressed by taking advantage of the birefringence induced by the intense main pulse in the fiber itself [13, 14].

Until recently, all theoretical and experimental studies of soliton compression were focused on normal single-mode fibers [11], which exhibit anomalous dispersion only for wavelengths larger than $1\text{ }\mu\text{m}$, as well as a relatively low nonlinearity. The introduction of highly nonlinear photonic crystal fibers (PCFs) [15] and photonics nanowires having anomalous dispersion

at visible and near infrared wavelengths has shed a new light on this field, in particular in view of the possibility of applying soliton compression techniques to the pulses emitted by today's most common ultrafast lasers, such as Ti:sapphire and Cr:LISAF oscillators.

Specifically, the broad region of anomalous group delay dispersion (which for photonic nanowires extends into the visible spectral region) allows for the efficient compression of pulses in the 800 nm region, as recently demonstrated by Foster et al. [16], who experimentally achieved pulse compression of low-energy pulses from 70 fs down to 6.8 fs in photonic nanowires, and theoretically predicted pulses as short as one single optical cycle. Even if photonic nanowires can exhibit flatter dispersion profiles in the visible and near-infrared regions than most PCFs, their use still poses difficulties, mostly due to their small dimensions, delicate construction, and implementation. On the other hand, PCFs with core sizes of around $1.5\text{ }\mu\text{m}$ and a high nonlinearity are readily available. In a recent work, Bessonov et al. [17] theoretically investigated solitonic propagation and compression of high-energy laser pulses in hollow photonic crystal fibers, where pulse durations down to 10 fs at wavelengths of around $1\text{ }\mu\text{m}$ were predicted. However, to our knowledge, soliton self-compression of low-energy 800 nm ultrashort pulses in highly nonlinear PCFs and in the few-cycle regime has not been studied so far.

In this work we investigate the possibility of efficient self-compression of low-energy laser pulses down to the few-cycle regime using a commercially available highly-nonlinear PCF.

We perform a systematic numerical study, based on a generalized nonlinear Schrödinger equation that includes higher-order dispersion terms, delayed Raman response and self-steepening, to identify the most relevant parameters that determine the compression limit. A detailed comparison between different approximations to nonlinear pulse propagation is made, in order to better isolate the detrimental effects that more strongly affect the compression process, which shows that pulses with durations as short as 4 fs can be directly obtained by propagating linearly chirped or transform limited low-energy pulses generated from a typical (30 – 100 fs) ultrafast Ti:sapphire oscillator in a PCF without the need of additional compression methods, which may result in novel and compact devices for the generation of laser pulses in the few-cycle regime.

We believe that this study will be very helpful for predicting the output of actual experiments based on this technique.

II. MODEL DESCRIPTION

In our model, an ultrafast laser pulse as directly generated from a typical (30 – 100 fs) commercially available Ti:sapphire laser oscillator is coupled to a highly-nonlinear PCF of length L . The propagation equation along the longitudinal fiber direction z for an electric field envelope $A(z, t)$ of central frequency ω_0 and in the plane wave approximation is given by:

$$\frac{\partial A(z, t)}{\partial z} = i \int_{-\infty}^{+\infty} \beta(\omega) \tilde{A}(z, \omega) e^{-i\omega t} d\omega + iB[A(z, t), t], \quad (1)$$

where $\tilde{A}(z, \omega)$ is the spectral field amplitude,

$$\beta(\omega) = \sum_{n=2}^{+\infty} \beta_n(\omega_0) (\omega - \omega_0)^n \quad (2)$$

is the phase distortion, with $\beta_n(\omega) = \partial \beta(\omega) / \partial \omega$ the n th-order dispersion, and

$$B[A(z, t), t] = \gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t}\right) (A(z, t) \int_0^{+\infty} R(t') |A(z, t - t')|^2 dt') \quad (3)$$

is the nonlinear term with γ the nonlinearity coefficient and $R(t)$ the nonlinear response function. The functional form of $R(t)$ can be written as [11]

$$R(t) = (1 - f_R) \delta(t) + f_R h_R(t), \quad (4)$$

where f_R is the fractional contribution of the delayed Raman response function $h_R(t)$, which can be expressed as:

$$h_R(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp(-t/\tau_2) \sin(t/\tau_1), \quad (5)$$

where τ_1 and τ_2 are two adjustable parameters. Numerical values of $f_R = 0.18$, $\tau_1 = 12.2$ fs and $\tau_2 = 32$ fs are chosen to provide a good fit to the measured Raman gain spectrum of fused silica [11]. The Generalized Nonlinear Schrödinger Equation (GNSE) (1) includes both self-steepening and the delayed Raman effect [11] and accurately describes pulse propagation of few nJ pulses in PCFs down to the single cycle regime in the framework of the Slowly Evolving Wave Approximation (SEWA), which requires that the envelope and its phase do not vary *significantly* as the pulse covers a distance equal to its central wavelength $\lambda_0 = 2\pi c/\omega_0$ [18]. In the hypothesis of *negligible* third-order

dispersion ($\beta(\omega) \simeq 1/2\beta_2(\omega_0)(\omega - \omega_0)^2$), self-steepening, and delayed Raman response ($B \simeq \gamma A(z, t)|A(z, t)|^2$), equation (1) reduces to the Nonlinear Schrödinger Equation (NSE), suitable for describing pulse propagation in the picosecond or even sub-picosecond temporal regime [11], provided that third- and higher-order dispersion terms can be neglected and pulse duration is significantly longer than the delayed Raman response of the medium, $T_R = \int_0^{+\infty} tR(t)dt \approx 5$ fs (for fused silica). The fiber parameters are those of a *commercial* highly-nonlinear PCF (BlazePhotonics NL-1.6-670) already available in our laboratory and which we plan to use in a forthcoming experiment: $L = 5$ mm, $\gamma = 139 \text{ W}^{-1} \text{ mm}^{-1}$, and a group velocity dispersion (β_2) profile as shown in figure 1.

III. SOLITON-EFFECT COMPRESSION

Soliton-effect compression relies on propagation properties of optical solitons which are generated in nonlinear fibers in the anomalous dispersion regime [11]. In particular, solitons of order $N \geq 2$ always change their shape periodically as they propagate inside the fiber and in general experience an initial pulse narrowing phase, which can be exploited to obtain pulse compression once a proper fiber length is chosen [11]. The optimal fiber length z_{opt} and the compression factor F_c can be estimated from the following empirical relations obtained in the framework of the NSE [11]:

$$F_c \simeq 4.1 N \quad (6)$$

$$z_{opt} \simeq \left(\frac{0.32}{N} + \frac{1.1}{N^2} \right) z_0, \quad (7)$$

where $N = \sqrt{L_D/L_{NL}}$ is the soliton order, $L_D \simeq 0.321 \times T_{in}^2/\beta_2$ is the dispersion length, $L_{NL} = (\gamma P_0)^{-1}$ is the nonlinear length, $z_0 = \frac{\pi}{2} L_D$ is the soliton period, T_{in} is the pulse initial full-width-at-half-maximum (FWHM) duration, and P_0 is the peak power of the initial pulse. In general, the compressed pulses exhibit a broad pedestal whose origin is due to the fact that the nonlinearity induces a linear chirp only over the central part of the pulse, which is the only part that can be efficiently compressed by the fiber anomalous group velocity dispersion [11]. The quality factor Q_c , defined as the fraction of the total energy contained in the compressed pulse, is always less than unity and scales as the inverse of the compression factor F_c [11]. Equations (7) predict an indefinitely increasing compression factor for an initial fixed pulse temporal profile with increasing peak power, once a proper fiber length is

chosen. However, equations (7) are obtained by integrating the NSE, which fails to be valid in the few femtosecond temporal regime, so the GNSE has to be used instead.

IV. RESULTS AND DISCUSSION

The best conditions for soliton pulse compression were obtained starting from a 30 fs initial Fourier transform-limited (TL) gaussian pulse with central wavelength $\lambda_0 = 800$ nm, which can be generated from the ultrafast Ti:sapphire laser oscillator we intend to use in our future experiment [19, 20]. Our numerical study shows that a typical 30 fs few-nJ femtosecond pulse requires an optimum fiber length considerably shorter than 5 mm, which immediately poses a practical problem as it is very difficult to obtain such short fiber lengths. However, this length can be increased if the initial pulse duration is made larger for the same pulse energy and we found that initial pulse durations of around 100 fs readily allow to overcome this difficulty. Therefore, we chose to introduce a positive linear dispersive material to temporally broaden the initial 30 fs pulse so as to produce the optimal pulse peak intensity and temporal width at the fiber input (see figure 2). We also found that this method resulted in the same compressed pulse as if the spectral width (hence temporal duration) of the initial TL pulse was varied instead. The former method was nevertheless preferred to the latter, as in principle it permits arbitrarily large extra-cavity pulse stretching while retaining the initial pulse spectrum generated from the laser oscillator, hence avoiding disturbances to the laser parameters and mode-locking stability.

Figure 3 shows the spectrum, the spectral phase and the temporal profile of the pulse (a) at the fiber input, and for fiber lengths of (b) $z = 4$ mm, (c) $z = 5$ mm, and (d) $z = 6$ mm, assuming an initial pulse energy $E = 5 \times 10^{-10}$ J and a pulse duration broadened to 119 fs in a normal positively dispersive medium such as a piece of glass, so as to obtain an optimized compressed pulse for $L = 5$ mm under the condition that the most intense pre/post-pulse has an intensity lower than 0.3 times the pulse peak value. It can be observed that the compression process mostly acts upon the central part of the pulse temporal profile, while maintaining a broad uncompressed pedestal, until a pulse FWHM duration $T_f = 3.7$ fs and a quality factor $Q_c = 0.32$ are reached. The central wavelength of the resulting broadened spectrum does not deviate significantly from 800 nm, and so the compressed pulse is less than two cycles in duration. For $z > 5$ mm (see figure 3 (d) and (e)) the pulse temporal

profile presents an increasing multi-peak and broadened structure. The asymmetric spectral profile, larger in the *blue* side, and the steeper temporal trailing edge shown in figure 3 (c) are those typical of self-steepening, while Raman scattering is characterized by a shift of the pulse spectrum towards lower frequencies, which is associated with a temporal delay of the pulse [11]. In figure 4 the spatial evolution of the temporal pulse width, the quality factor and the relative intensity of the largest secondary pre/post pulse are reported, showing how the pulse compression process is always associated with a reduction in pulse *quality*. The behavior shown in figures 3 and 4 differs from the soliton pulse evolution predicted by the NSE as the higher-order dispersion and nonlinear effects included in the GNSE destroy the periodical evolution typical of high-order solitons. A systematical numerical study was performed to identify which processes have the most detrimental effect in the pulse compression process. Figures 5 (a) and (b) show the final temporal width and the quality factor as a function of the pulse energy, obtained by integrating the GNSE (curves (1)), neglecting higher-order dispersion (curves (2)), neglecting self-steepening and delayed Raman response (curves (3)), and integrating the NSE (curves (4)). The reported values correspond to the narrowest obtainable pulse with a pre/post pulse relative intensity lower than 0.3. It can be noticed that higher-order dispersion terms have the most detrimental effect in the compressed pulses, making curves (1) and (2) in figure 4 (a) go through a minimum value and therefore deviating from the monotone behavior predicted by relations (7) and confirmed by curves (3) and (4). In this view the way of increasing the pulse compression effect mostly relies on using a nonlinear fiber with the flattest possible group velocity dispersion. These results are reminiscent of those obtained for longer pulse durations in the 100 fs range [21]. In the ideal hypothesis of a completely flat group velocity dispersion profile, for the same pulse energy and temporal width of figure 3, a compressed single-cycle pulse with $T_f = 2.5$ fs and $Q_c = 0.34$ can be obtained (see figure 6). The need of additional dispersive polarization elements that introduce significant pulse broadening prevents the direct application of standard nonlinear birefringe methods to suppress the observed broad pedestal found in soliton compressed pulses. The pedestal could nevertheless be partially suppressed by simply focusing the pulses in a thin ($100 - 300 \mu\text{m}$), low-dispersion near infrared low-bandpass filter, which can act as an efficient saturable absorber for femtosecond pulses [22].

V. CONCLUSIONS

In conclusion, we numerically demonstrate the feasibility of efficient soliton compression of transform-limited or linearly chirped ultrashort laser pulses down to the sub-2-cycle regime using a standard Ti:sapphire oscillator and a 5-mm long commercially available PCF. An optimized 3.7 fs pulse can be obtained from an initial ultrashort laser pulse centered at 800 nm, with duration in the 100–fs range and an energy of 0.5 nJ, while longer pulses can also be compressed at slightly higher pulse energies of a few nJ. We identify high-order dispersion as the most relevant detrimental factor in few-cycle soliton compression, showing that single-cycle pulses with 2.5 fs can be obtained for the ideal case of a PCF with a completely flat dispersion profile. We believe that this technique could be the basis for novel, compact and efficient sources of few-cycle laser pulses based on a standard ultrafast oscillator coupled to a properly chosen PCF and a simple pulse cleaner, which could have a great impact in the scientific community.

VI. ACKNOWLEDGMENTS

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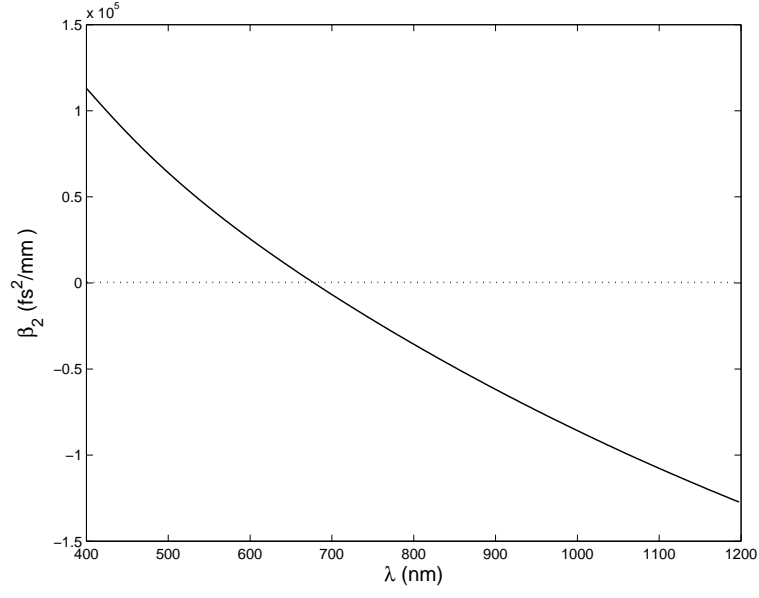


FIG. 1: Group velocity dispersion of the highly-nonlinear PCF BlazePhotonics NL-1.6-670 (obtained from the manufacturer's data).

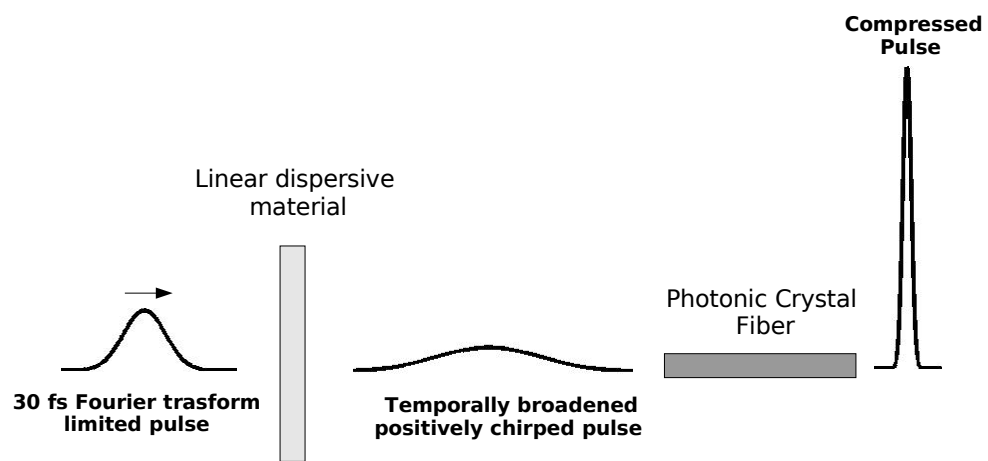


FIG. 2: Scheme of the compression process.

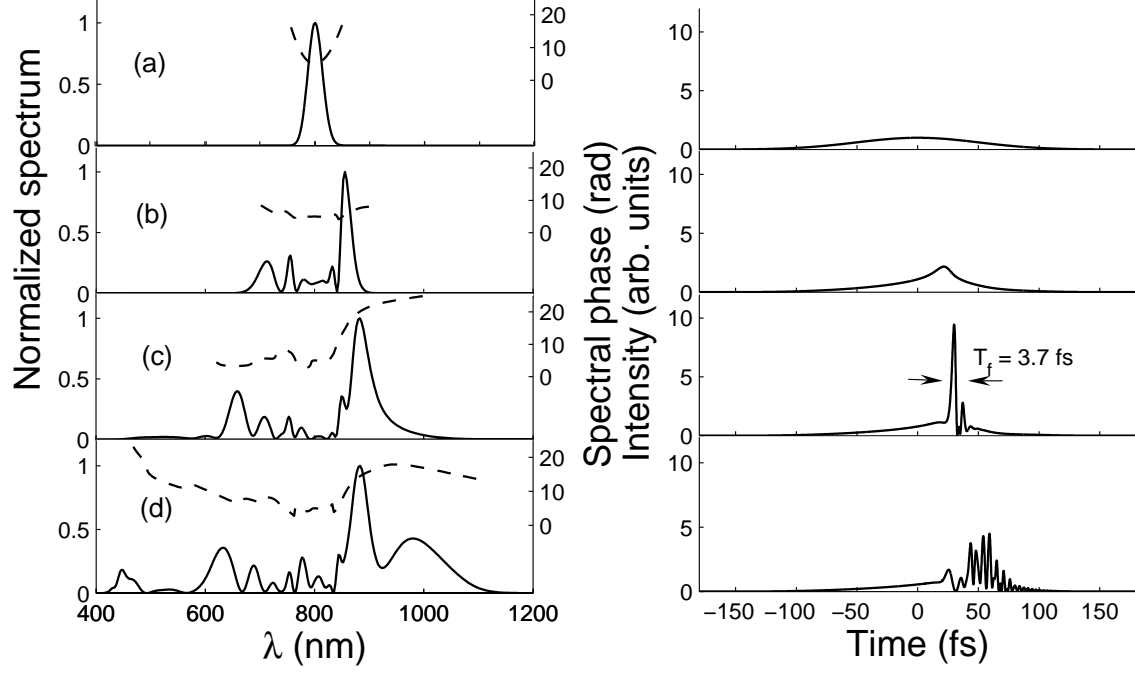


FIG. 3: Spectra, spectral phases, and temporal profiles corresponding to (a) $z = 0$, (b) $z = 4$ mm, (c) $z = 5$ mm, (d) $z = 6$ mm for a 30 fs laser pulse of initial energy $E = 5 \times 10^{-10}$ J that has been temporally broadened to 119 fs.

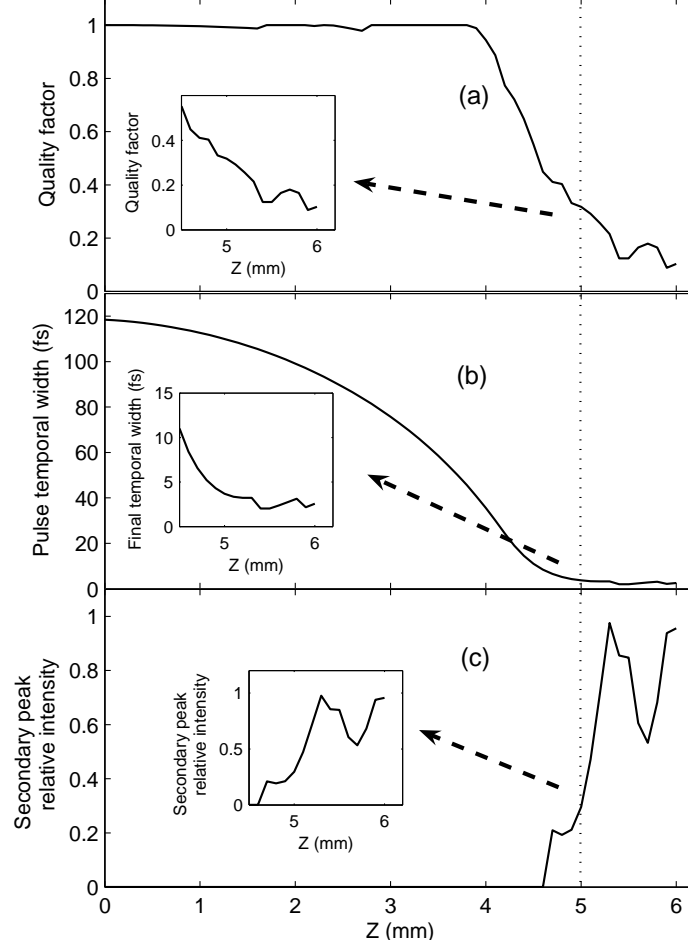


FIG. 4: (a) Quality factor, (b) temporal width, and (c) relative intensity of the secondary peak as a function of propagation distance inside the PCF for the same initial pulse of figure 3. The dotted vertical line denotes the fiber length.

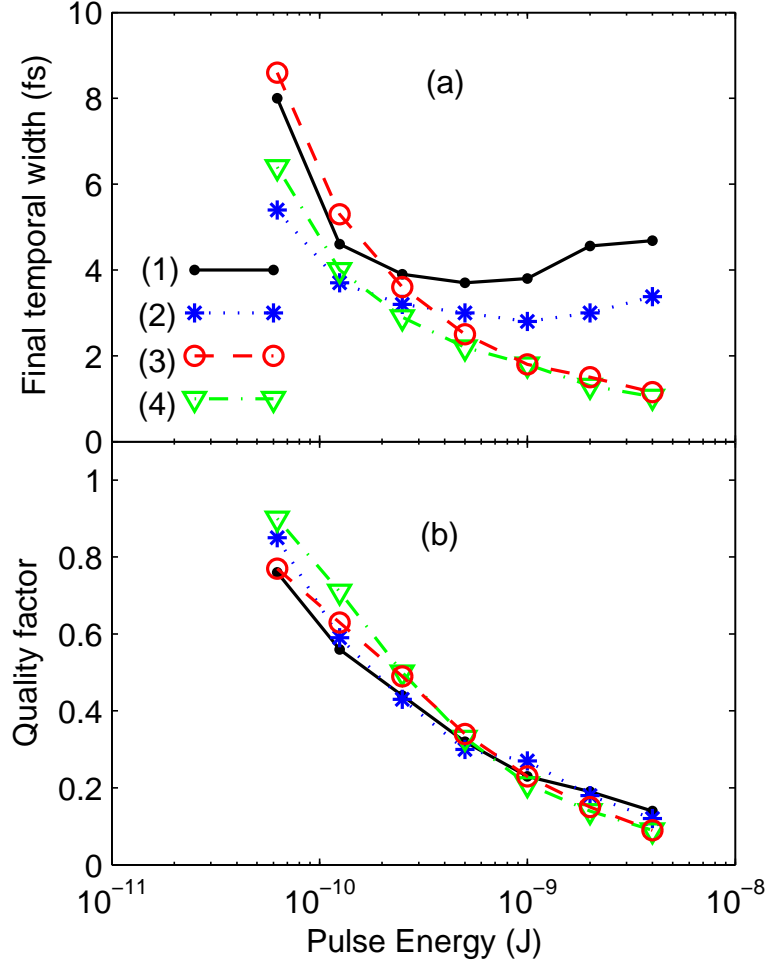


FIG. 5: (Color online) (a) Minimum final temporal width and (b) quality factor as a function of the initial pulse energy obtained by integrating the GNSE (curves (1)), neglecting higher-order dispersion (curves (2)), neglecting self-steepening and delayed Raman response (curves (3)), and integrating the NSE (curves (4)). The reported values correspond to the narrowest obtainable pulse with a pre/post pulse intensity lower than 0.3 times the pulse peak value.

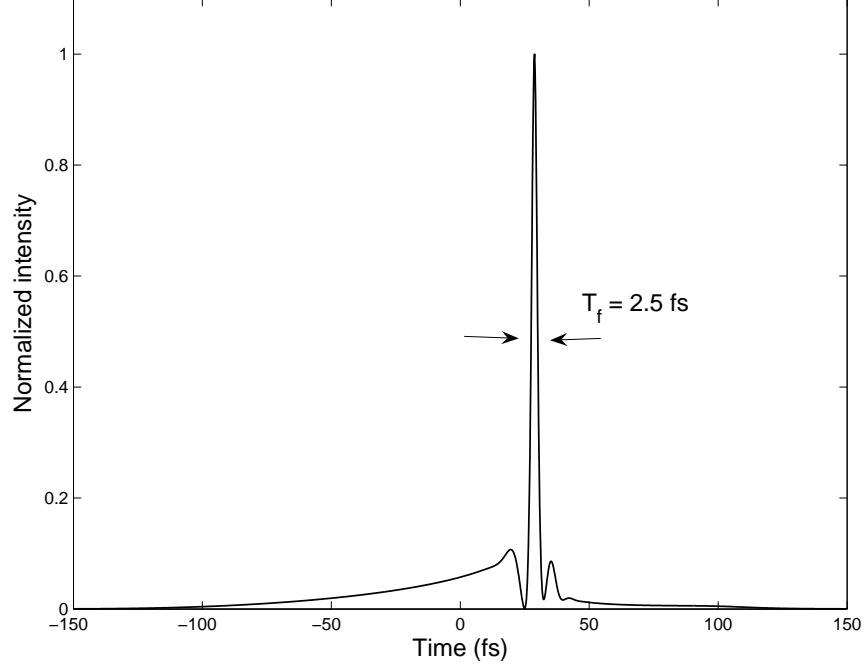


FIG. 6: Single-cycle pulse obtained for the same initial pulse of figures 3 and 4, in the hypothesis of a *completely* flat dispersion profile, i.e. $\beta(\omega) \simeq 1/2\beta_2(\omega_0)(\omega - \omega_0)^2$.